Luminosity Distributions within Rich Clusters - I: A Ubiquitous Dwarf-Rich Luminosity Function ?

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Abstract

From deep CCD observations of the cluster Abell 2554 we have recovered the cluster's luminosity distribution over a wide range of magnitude ($-24 < M_R < -16$). We compare the derived A 2554 cluster luminosity function (at redshift 0.1) with that of the local Coma Cluster (A 1656) and the more distant ($z = 0.2$) cluster A 963. The distribution is remarkably similar for these three clusters of comparable richness and morphology. All show a flat ($\alpha = -1.0$) luminosity function for the giant galaxies ($-24 < M_R < -19.5$) which exhibits a sharp upturn ($\alpha \approx -1.7$) at some intermediate magnitude ($M_R \simeq -19$) and continues to rise to the limits of existing data. We suggest that such a luminosity function may be ubiquitous among rich clusters and that a similar form may apply for poorer clusters and possibly the field as well. The three cluster dwarf LFs are seen over a range of lookback times covering a quarter of the age of the universe. Therefore the similarity between the three measured LFs seems to rule out strong evolution of the dwarf populations in rich cluster environments, at least out to z = 0.2, unless richness effects conspire to conceal evolutionary changes.

Keywords: galaxies: clusters: individual: A2554 - galaxies: photometry - galaxies: luminosity function, mass function - galaxies:evolution.

1 Introduction

There has recently been a renewal of interest in the galaxy luminosity function (LF), in particular in its faint end. This has been driven partly by improved data (ie. we can now observe fainter galaxies; see eg., Bernstein *et al.* 1995), partly by increased interest in dwarf galaxies and their number density *per se* (eg., Ferguson & Binggeli 1995), and partly by the recognition that low luminosity galaxies and their evolution almost certainly play a vital cosmological role in, for example, explaining the large numbers of galaxies counted at faint magnitudes (eg., Phillipps & Driver 1995; Ellis *et al.* 1996).

Although in the most general context one would like to know the luminosity function of field galaxies to very faint levels, this is observationally limited, primarily by the requirement for individual redshifts and by the unavoidable predominance of brighter galaxies in magnitude limited samples (see Driver & Phillipps 1996). One may also worry about the possible selection effects in the faint end of the local field LF (McGaugh 1994; Schade & Ferguson 1994; Phillipps & Driver 1995). One is therefore led to determinations of the LF of rich clusters of galaxies and several groups have recently presented cluster LFs down to absolute magnitudes previously sampled only in our immediate neighbourhood (see Thompson & Gregory 1993; Driver *et al.* 1994b; Bernstein *et al.* 1995; De Propris *et al.* 1995). Here we add to these recent results via a deep CCD imaging survey of the cluster Abell 2554 which allows us to determine the LF to over 6 magnitudes below the characteristic magnitude of giant galaxies (ie. $L = 0.003L_*$).

We also present a first attempt to examine the evolution of the rich cluster LF at faint levels. Very extensive redshift surveys carried out in the last few years (Ellis *et al.* 1996; Lilly *et al.* 1995) have supplied evidence for a change in the field galaxy LF - either steepening, shifting or both - for moderately low luminosity dwarfs (see also Broadhurst, Ellis & Shanks 1988; Colless 1995). Evidence - one way or the other - for evolution of cluster dwarfs is still lacking, however. The well-known Butcher-Oemler (1984) effect is primarily a spectroscopic or morphological evolution (eg., Couch & Sharples 1987) whose effect on the LF has not, to our knowledge, been investigated (though see Barger *et al.* 1996 for a related discussion). In any case, the known cases are restricted to fairly luminous galaxies. Here we discuss our new observations of A 2554 at redshift $z = 0.1$ and compare these with similar observations of A 963 ($z = 0.2$) (from Driver *et al.* 1994b) and published results on the Coma cluster at $z = 0.02$ (eg. Godwin & Peach 1977, Godwin, Metcalfe & Peach 1983). In a model with $\Omega = 1$, $H_0 = 50\text{km s}^{-1}\text{Mpc}^{-1}$ (ie. $h = 0.5$ in the usual notation), as assumed herein for consistency with previous work, this gives us

a range in look back times of a quarter of the age of the universe or $\simeq 3.3$ Gyr.

In Section 2 we describe the observations and data analysis whilst in Section 3 we detail the recovery of the LF of A2554. Section 4 describes our analysis of the structure of A2554 and in Section 5 how this cluster compares with other clusters whose LFs are known. Section 6 contains a brief description of the relevance of these observations to the evolutionary scenarios explaining dwarf galaxy evolution and the faint blue galaxy excess seen in the number counts.

2 The Data

2.1 Observations

A 2554 ($23^h\ 09^m\ 48^s, -21^o\ 45'$) is a richness class 3 cluster of Bautz-Morgan type II: at $z = 0.106$ (Abell 1958; Leir & van den Berg 1975; Abell, Corwin & Olowin 1989). The observations were taken by RMS in 1994 July at the Anglo-Australian Telescope, as part of a larger programme of cluster photometry (see Phillipps, Driver & Smith 1995a,b). Data were obtained using the f/1 focal reducing optics and 1024×1024 pixel Thomson CCD (see eg., Turner *et al.* 1993 for details of this system). The pixel size is $0.98''$ giving a total field of view $17'$ square. Note that this corresponds to almost exactly 3 Mpc at the cluster distance (600 Mpc for our choice of cosmological parameters). A grey scale representation of our image of A 2554 is shown in figure 1. The seeing for this exposure was 2".

Multiple short exposures (75 or 100 seconds each) were obtained to aid defect removal and flat fielding. Frames were 'jittered' by 10 arcseconds between exposures to minimize systematic effects on the pixel scale. The total exposure time was 4850 seconds in the Kron-Cousins R band. After standard bias subtraction, a master flat field was constructed from a median stack of all the disregistered cluster frames (both for this cluster and for others observed in the same run), as in Driver *et al.* (1994a,b). After flattening by this master flat, the individual frames of the cluster area were registered and co-added. This reduces the pixel-to-pixel sky noise to near the level of the Poisson counting noise (0.5 %), but may leave residual larger scale variations in the background level which can be important for faint object detection (see eg., Davies *et al.* 1994). These variations were removed by subtracting a spatially median filtered version of the data (with box size 64 pixels), as discussed in Schwartzenberg *et al.* (1995). Region to region variations (say on arc minute scales) are then reduced to 0.2 % or less. Blank (ie. off cluster) frames,

including in particular ones in the well studied South Galactic Pole region (eg., Couch, Jurcevic & Boyle 1993), were also taken, during the same night and similar seeing, with an identical set-up as that for A 2554. The SGP field was reduced in exactly the same way as the cluster frames. Exposures of Landolt (1993) standard stars throughout the night showed that conditions were photometric to about 0.02 magnitudes. Conversion to the standard R_c system was also carried out using the stellar observations.

2.2 Image Detection

The resulting data frame was processed using the PISA image detection package in the STARLINK suite of astronomical data reduction software. This package utilizes a connected pixel algorithm to detect objects containing more than a limiting number of pixels above a user-defined threshold. Overlapping objects were split into their constituent objects using a deblending algorithm. To prevent this effect occurring in the haloes of bright stars, such regions, with a generous allowance for the outer low-level wings of the stellar profile, were excluded from the analysis. For this survey an isophotal magnitude was calculated using limits for the detection of at least 4 pixels in area, with each pixel above a limit of 1σ above sky (the sky 'noise' σ being determined directly from the histogram of pixel values). For the present data this threshold corresponds to 26.9 $R\mu$ (0.5% of sky, as noted earlier). After object detection, a further (conservative) 7.5σ cut was applied to eliminate possible noise 'objects' (cf. Driver *et al.* 1994b). This combination will *not* result in a magnitude limited sample unless all galaxies of a given apparent magnitude also all have the same surface brightness, or at least contrive not to extend into undetectable areas of parameter space (cf. the discussion in Driver *et al.* 1994a). In particular, fainter galaxy images have to be more compact in order to pass the signal-to-noise test. (Large diffuse images contain more sky noise). We should always bear this in mind when assessing the results, especially in comparisons between different data sets. This effect will lead to an underestimate of the steepness of the faint-end of the LF. This is supported by the work of Schwartzenberg (1996) on dwarf galaxies in the Virgo cluster who finds a steeper LF than presented here. Figure 2 shows all the detections (≥ 4 pixels) in the parameter space of isophotal area versus isophotal magnitude. Solid symbols indicate the detections with S/N ≥ 7.5. (The limit is simply a diagonal line in this plot). The upper line plotted on the figure is the ultimate selection limit for an image of a given number of pixels all at the detection threshold. As an indication of the intrinsic parameters involved, figure 2

also shows the loci of images (assumed to have perfect exponential profiles) of particular central surface brightnesses and scale sizes. (cf. Schwartzenberg *et al.* 1995). Note that the calculated parameters are not corrected for the effects of seeing or noise (discussed in Turner *et al.* 1993).

3 Recovering A 2554's Luminosity Distribution

Typically for deep CCD images a uniform correction factor is applied to convert the number of actual galaxies detected to the number per square degree. However, for cluster sight-lines an additional consideration is the obscuration of fainter galaxies by the brighter cluster members. In dense cluster environments a significant fraction (5-40%) of the field of view may be occupied by the more extended brighter cluster members, hence progressively fainter galaxies are sampled over a smaller field of view. Normally for field sight-lines this crowding effect is negligible at magnitudes significantly brighter than the confusion limit, due to the paucity of bright foreground galaxies. However this is not necessarily the case when dealing with cluster sight-lines and/or very faint galaxies and the importance of including this correction depends on the cluster's richness, redshift and morphology. The simplest way to account for this "diminishing area" effect is to determine the field-of-view correction for each individual galaxy, by summing the cumulative isophotal area covered by all brighter objects. This assumes that in the case where a faint foreground galaxy overlaps with a more luminous distant galaxy, the faint galaxy's luminosity is essentially lost; it will neither be detected itself nor is its luminosity likely to add significantly to that of the brighter galaxy (though see Bristow 1996 for a more detailed discussion of the effect of image overlap on galaxy counts).

Figure 3 shows the significance of this correction for both our A 2554 cluster and the SGP blank field sight-lines. We see that at $m_R = 23$ (our completeness limits) the field correction is 1.08 (filled triangles, *i.e.* 8% of the available field-of-view is occupied by galaxies with $m_R < 23$), while for the cluster the correction is 1.19 (filled squares, *i.e.* 19%). This correction is clearly significant, but this simple method of correcting ignores the radial distribution of the cluster galaxies. Given that the luminous galaxies are normally clustered around a central core then it follows that the central region is more likely to be obscured than the outer regions. Figure 3 therefore illustrates the required correction for the core region (short dashed) and that for an outer region close to the frame edges (long dashed). At $m_R = 23$ these are factors of 1.25 and 1.16 respectively (adopting an effective mean distance modulus to A2554 of, $D_{A2554} = 39.2$). That the outer

annulus still has a diminishing area correction greater than that of the blank field, implies that the cluster size is greater than our total field-of-view. The open squares shown in Figure 3 represent the ratio of radially corrected number-counts (using three radial ranges; core, surrounding annulus and edges) to non-corrected counts for the cluster sight-line. While this radial correction generally produces marginally higher counts than the uniform diminishing area correction, some additional scatter is introduced because of (a) limited number statistics and (b) the distribution of cluster galaxies not being perfectly circular. We therefore use the mean cluster area correction in what follows. The radial profile of A 2554 is discussed later in section 6.

The final corrected number-counts for the A 2554 field are shown in their usual form in Figure 4 (upper panel). The SGP field has also been uniformly corrected for the "diminishing area". Overlain, as a solid line on Fig. 4, is our best fit to the R-band counts from Metcalfe *et al.* (1995) corrected to R_c ($= r_F + 0.1$), *viz.* $logN = 0.377R_C - 4.615$. The SGP counts, our comparison field, lie marginally below those of Metcalfe *et al.* at the faintest limit. This is to be expected as Metcalfe *et al.*'s data reach to fainter isophotal detection thresholds and are hence less effected by surface brightness selection effects (ie. they include slightly lower surface brightness objects at a given magnitude). The A 2554 data and SGP data have essentially identical isophotal depth (and are both complete to $R \sim 22.5$ at least), so no (galaxy population dependent) corrections for surface brightness selection effects need to be considered.

In order to obtain the cluster-only galaxy counts and hence the LF we need to subtract the background counts (c.f. Driver *et al.* 1994b). We can do this in two ways. Firstly, we can assume that the background counts are well known. This has the advantage of minimal Poisson noise since we can use a best fit to the extensive published data, but may have systematic effects because of differences in detection procedures or from field to field fluctuations. Second, we can use our own 'blank' field to determine the background/foreground contamination. This has the obvious advantage of identical image detection and processing, but increases the Poisson noise (by about $\sqrt{2}$). It will also fail to remove the possibility of field to field variations, unless the line-of-sight is close to the line-of-sight of the cluster. In this case our reference blank SGP field lies approximately 15 degrees from A 2554. In addition to the two methods outlined above we could also use the variations in number density across our field itself to determine the background level. However for this method we would require a larger field-of-view (recall from Figure 3 that the outer radial correction for the diminishing area in A 2554 is still greater than that for the SGP field implying that the cluster population extends beyond the edge of

our field).

Figure 4 (lower panel) shows the application of the first two techniques, based on the counts of Metcalfe *et al.* (1995) and our SGP field respectively. The two methods imply closely similar results for the luminosity function of A 2554, with most of the discrepancy at either the very bright or very faint ends of the luminosity distribution. Overall the agreement is excellent, and within the errors of both analyses. Note that the errorbars include the assumption of Poissonion statistics in the numbers of detections added in quadrature to a uniform 10 % error. The latter allows for the possibility of a 0.1 magnitude systematic error in our photometric zero points and/or field-to-field variations in the background numbers.

The marginal discrepancies at the bright and faint ends can readily be explained. At bright magnitudes the SGP is more susceptible to field-to-field variations than the more extensive data given in Metcalfe *et al.*, due to the SGP field's small area. As noted above, at our faintest magnitudes the Metcalfe *et al.* data are liable to include some galaxies with surface brightnesses too low to be included in either the A 2554 or SGP data. Based on this, we can adopt a 'best buy' model which uses the A 2554 – Metcalfe data points for $M_R < -19.5$ and the A 2554 – SGP points for $-19.5 < M_R$. The solid line shows a flat Schechter (1976) function with $M_R = -22.3$, $\alpha = -1$ normalised to match the $M_R < -19.5$ data of A 2554 – Metcalfe.

If we do consider the excess number of galaxies in the central regions compared to the edges, then a rather similar shaped LF is recovered (though, of course, the normalization is not the same as we are subtracting off some cluster members), up until the point where the small number statistics begin to dominate. Apart from confirming the steep dwarf part of the LF, this also indicates that the radial fall-off for different luminosity galaxies is not all that dissimilar (ie. little luminosity segregation).

4 The Morphological Structure of A 2554

Figure 5 shows the radial distribution of cluster galaxies about the cluster centre, divided into two magnitude intervals. These intervals have been chosen such that the sample is divided at the point where the luminosity distribution shows the distinctive upturn. The radial profile of the more luminous galaxies rapidly drops off away from the centre but does not reach the density of the field within our field-of-view. (In fact the cluster probably has a more complex underlying structure than a simple isothermal sphere, see below). The less luminous galaxies also show a gradual fall-off towards the frame edges

but less so than the giants.

We might worry slightly that the dwarf population seems to follow a flatter distribution, as this is precisely what one would expect if we had underestimated the background subtraction due, for example, to a zero point shift in our cluster field calibration. (Since the cluster galaxy numbers increase less quickly than the background counts, background errors have a larger effect at faint magnitudes). In order to examine the morphological structure of the cluster in a little more detail, Figure 6 shows the number-density enhancement across the field of view for the giants ($14.0 < R < 20.0$) and dwarfs ($20.0 < R < 22.75$) in turn (Figs. 6a and 6b respectively).

The gray scale plots show the excess number of galaxies over the mean field value for the bright cluster galaxies (a), bright field galaxies (b), faint cluster galaxies (c) and faint field galaxies (d). The grayscales are scaled from the mean field value to the mean field value plus 48.0 galaxies per 200×200 pixel cell. The isodensity contour lines are set to: +6.0, +12.0, +18.0, +24.0, +30.0, +36.0 and +42.0 excess galaxies per 200×200 pixel cell (Figs 6(a) and (c)) and +18.0, +30.0, +42.0, +48.0, +54.0, +60.0 and +66.0 excess galaxies per 200×200 pixel cell (Figs 6(b) and (d), scale up by ~ 300 to get to excess galaxies per sq deg).

Figure 6a therefore shows the 2-D distribution of the cluster giants which is seen to be non-symmetrical and to contain significant density structure out to the frame edges. For comparison Fig 6b shows the equivalent plot for the SGP field where minimal structure is expected (and seen). Fig. 6c shows the dwarf distribution which closely follows the distribution of the giants (note the main central peak and extensions towards the top and right-side). The equivalent density plot for the fainter field galaxies (Fig 6d.) shows that both the density and structure of the dwarf distribution in A 2554 are indeed significant. We therefore conclude that the dwarf galaxies follow the distribution for giants, at least approximately, and that background subtraction errors are not responsible for the large number of dwarfs seen. The distribution of dwarfs compared to giants in rich clusters place constraints on the various models of cluster evolution (such as galaxy harassment, Moore et al (1995)). The effect determined here is unfortunately only suggestive and a more detailed analysis, with data out to beyond the cluster radius, is required before any definite conclusions can be drawn (eg. Morshidi et al. 1995).

5 Comparison With Other Clusters

In a previous paper (Driver *et al.* 1994b) a similar technique was applied to observations of the cluster A 963, based on data taken with the Hitchhiker parallel CCD camera on the William Herschel Telescope at La Palma. The A 963 data had the disadvantage of the cluster and blank fields being taken a few weeks apart and under non-perfect conditions. Nevertheless the photometry for A 963 was shown to be consistent within a combined random error of 0.1 mag to the overlapping data of Butcher, Oemler & Wells (1983). A 963 lies at $z = 0.206$ and is of richness class 3, the same as A 2554. Figure 7 shows the new A 2554 result overlaid with the A 963 data. The normalization has been adjusted to give equal numbers in the well determined giant region between $M_R = -22.5$ and -20.5.

Also shown on Figure 7 is data for Coma, the most comparable nearby ($z = 0.024$) cluster in terms of richness, taken from Godwin & Peach (1977) and also Thompson & Gregory (1993). The Coma data, given in V and b_J respectively, has been corrected to the R_C-band by the assumption of constant colour dependencies of; $(V - R_C) = 0.4$, and $(b_J - R_C) = 1.7$ (based on the tabulated colours for ellipticals as listed in Driver *et al.* 1994a). For the three clusters shown in Figure 7, we have effective distance moduli $D_{Coma} = 35.8$, $D_{A2554} = 39.2$ and $D_{A963} = 40.8$, including uniform k-corrections of $1.5z$ (c.f. Driver *et al.* 1994a), the differential k-corrections between galaxy types being minimal for the R band at low redshifts.

It is worthwhile digressing momentarily to discuss the other recent data on Coma by Bernstein *et al.* (1995) and Biviano *et al.* (1995), these two papers both study the core region of the cluster and find a somewhat flatter LF than that seen by Godwin & Peach (1977) and Thompson & Gregory (1993). Comparing the LFs from these four published surveys seems to show a strong environmental dependency, with the studies of the core regions revealing typically flatter LFs than the wider field of view surveys[1] This picture is consistent with the results shown for A2554 in Figure 5, whereby a significantly steeper density profile for the more luminous cluster members is seen. Clearly to derive a cluster's total LF it is important to survey over a significant fraction of the cluster's total extent. Hence here we use the Thompson & Gregory sample for our local comparison as the

[1] The survey sizes are: 497 galaxies ($V < 17.5$, $M_R < -18.5$) within 1.22 sq deg for Godwin & Peach (1977); 1158 galaxies ($b_J < 20.0$, $M_R < -17.5$) within 3.97 sq deg for Thompson & Gregory (1993); 265 galaxies ($b_J < 18.0$, $M_R < -19.0$) within 0.33 sq deg for Biviano *et al.* (1995); and, ~ 1490 galaxies ($R < 25.5$, $M_R < -11.0$) within 0.015 sq deg for Bernstein *et al.*. (1995). Note in particular that only ~ 45 galaxies from the Bernstein CCD sample are contained in the overlap range with our data ($-24 < M_R < -16$).

sample size (over the relevant absolute magnitude range) and field-of-view are largest.

The three data sets for the three clusters shon in Figure 7 (spanning a range of redshift $z = 0.02 - 0.2$) for similar richness clusters can be seen to show a very strong similarity, with a strong up turn at about $M_R = -19$ and a steep slope $\alpha \simeq -1.5$ faintwards of that point. (Note that $M_R = -19$ corresponds to about $M_B = -16 + 5$ $\log h$, the conventional giant/dwarf boundary). In conjunction with other recent work on rich clusters, particularly that of De Propris *et al.* (1995), this tentatively suggests that this form of the luminosity distribution of rich clusters may be ubiquitous. It is arguably best described by the sum of two individual luminosity functions for the separate giant and dwarf populations. The lines shown on Figure 7 represent a Schechter (1976) function for the giants with parameters $M_R^* = -22.3$, $\alpha = -1.0$ (cf. Efstathou et al 1988) and a dwarf Schechter function with parameters $\phi_*(\text{Dwarfs}) = 1.5 \times \phi_*(\text{Giants})$, $M_R^* = -18.8$, $\alpha = -1.7$. While we contend that a two component luminosity function provides a more appropriate fit (see also Biviano *et al.* 1995; Lobo *et al.* 1995), a single luminosity function with slope $\alpha \simeq -1.5$ (not shown) can also provide a reasonable description (see Bernstein *et al.* 1995). [The reader is recommended to freely adopt either description within the bounds defined by Figure 7, but to beware that they give significantly different extrapolations/implications at fainter magnitudes, illustrating the peril of extrapolating any luminosity function beyond the limits of the available data.]

Marzke *et al.* (1994a,b) have recently presented evidence that the field galaxy LF may also show a turn up to a steeper slope at faint magnitudes (see also Keele & Wu 1995, and the discussion in Driver & Phillipps 1996, though see also Ellis *et al.* 1996 for a contrary view). The luminosity functions of other poorer clusters (Ferguson & Sandage 1991) and especially the well studied Virgo Cluster (Sandage, Binggeli & Tammann 1985; Binggeli, Sandage & Tammann 1988) also present clear evidence for both the separate population LFs and the overall steep slope at the faint end.

6 Evolution

As noted, the above LFs show a remarkable similarity, with no significant difference in the magnitude at which the steep slope cuts in. We can thus, very tentatively (given a sample of only 3 clusters), say that they do not show any clear evidence for evolution with cosmic epoch over the last quarter of the age of the universe (3.3 Gyr since $z = 0.2$ in our assumed cosmology). Of course, we should remember that the form of the LF may be conspiring to hide evolution of the dwarfs. If the dwarf component happened to be less numerous,

but brighter, in our more distant clusters, then the two effects would cancel out in the observed LF (since we see only the power law tail of the dwarf luminosity distribution). Observations of further clusters of different morphological types or densities should help to clarify this (cf. Ferguson & Sandage 1991; Turner *et al.* 1993).

To estimate the size of effect that might be measurable, we can shift the points for A 963 (the most distant cluster) by amounts Δm until they become inconsistent with the line defined by the nearer clusters. A shift (ie. assumed fading) of 0.4 magnitudes would put all the A 963 points (in the dwarf dominated region) significantly to the faint side of the line, so this should be readily detectable. How much might we expect? Two possible cases can be considered. If the light is dominated by old stellar populations (eg. dwarf ellipticals), then a reasonable estimate can be made via simple models of elliptical galaxy evolution, originally due to Gunn & Tinsley (1972). In this case red giants are taken to supply most of the luminosity so the evolution depends on the varying number of these as stars progressively turn off the main sequence. For a Salpeter like stellar initial mass function, a good approximation is $L \propto (t - t_{form})^{2/3}$ or for our model (and early t_{form}) $\Delta M \simeq -2.5log(1+z)$. Thus by $z = 0.2$ we expect 0.2 magnitudes brightening. This level of evolution is also seen in the much more sophisticated passive evolution models of, eg., Bruzual & Charlot (1993). If, instead, the dwarf galaxies are fading irregulars, then we might expect rather more evolution (eg. Davies & Phillipps 1988), though this will still be tempered by our observing at red wavelengths. If we set t_{form} in the above equation to correspond to, say, $z \simeq 0.5$, or use the Bruzual & Charlot models to look at the evolution over the first few Gyr after a starburst ends, then we might expect $\simeq 0.^m6$ of evolution since $z = 0.2$ (3.3 Gyr ago).

The latter fading irregular model has previously been successfully used to solve the problem of the steep galaxy number counts at faint magnitudes and the corresponding redshift distributions (see Phillipps & Driver 1995 and references therein). Furthermore, evolution of the field LF in line with this model has been observed in deep redshift surveys (Lilly *et al.* 1995; Ellis *et al.* 1996). It would thus be of interest if a larger sample of clusters continued to show no evidence for evolution at that level, suggesting a different (recent) evolutionary path for dwarf galaxies in cluster and field environments (eg. Moore, Katz & Lake 1996).

7 Summary

We have traced the LF of the cluster A 2554 (at $z = 0.1$) down to a level of $M_R \simeq -16$ (for $H_0 = 50$ km s^{-1} Mpc^{-1}), or about $3 \times 10^{-3} L_*$. The LF shows the characteristic upturn at $M_R \simeq -19$ seen in previous cluster observations. The overall LF can be well fitted by two (Schechter type) components, the giants having the conventional $\alpha \simeq -1$, the dwarfs a steeper $\alpha \simeq -1.7$. An alternative fit with a single $\alpha \simeq -1.5$ is also possible within the errors.

The comparison with the LFs for Coma ($z = 0.02$) and A 963 ($z = 0.2$) shows a remarkable similarity, suggesting (a) a ubiquitous dwarf population in rich clusters and (b) no evidence for significant evolution of the cluster dwarfs (at least at red wavelengths) over the last 3.3 Gyr. The level of evolution expected if cluster dIs have evolved to dEs since $z \simeq 0.5$, as required in some successful models of the evolution of their counterparts in the field, should be detectable in this type of data, though passive evolution probably would not.

In subsequent papers we will consider a further large sample ($\sim$ 15) rich clusters, observed to similar depths to the A 2554 data presented here. With the full set of clusters we will be able to investigate whether the steep slope cuts in at the same absolute magnitude in each case. If it does not, it will be of great interest to see whether the point where dwarf domination starts changes systematically with z. Of course, as pointed out earlier, if the LF really is of two component form, then the point where the steepening takes place depends on both the characteristic luminosity for the dwarfs (which might evolve) *and* on the ratio of dwarfs to giants in the cluster (which might change with cluster properties). In particular it will be important to see whether the Bautz-Morgan type (effectively an indicator of cluster density as opposed to richness) influences the dwarf to giant ratio *at given* z and hence the overall shape of the LF.

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Figures

Figure 1. Grey scale representation of the AAT field around Abell 2554. The 17′ field of view here corresponds to about 3 Mpc.

Figure 2. Isophotal area versus isophotal magnitude plot for all detected images in the A 2554 frame. The selection limits of 4 pixels (dashed line) and 7.5σ (solid line) are also shown, together with the loci of galaxies with scale size of 2arcsec (dotted line).

Figure 3. The correction required for the diminishing area available to faint objects because of the area occupied by brighter objects. Note that the cluster correction (solid squares) is significantly greater than the field correction (solid triangles). The lines show the correction for the core (short dashed) and outer regions (long dashed) of the cluster sight-line demonstrating that the distribution of cluster galaxies is concentrated towards the field centre.

Figure 4. (upper panel) R-band number-counts for A 2554 (solid squares) and SGP (open squares). Also shown (solid line) is our best fit line to the data of Metcalfe *et al.* (1995) corrected to R_c. (lower panel) The derived luminosity function for A 2554 by subtraction of the SGP data (filled squares) and by the Metcalfe et al data (filled triangles).

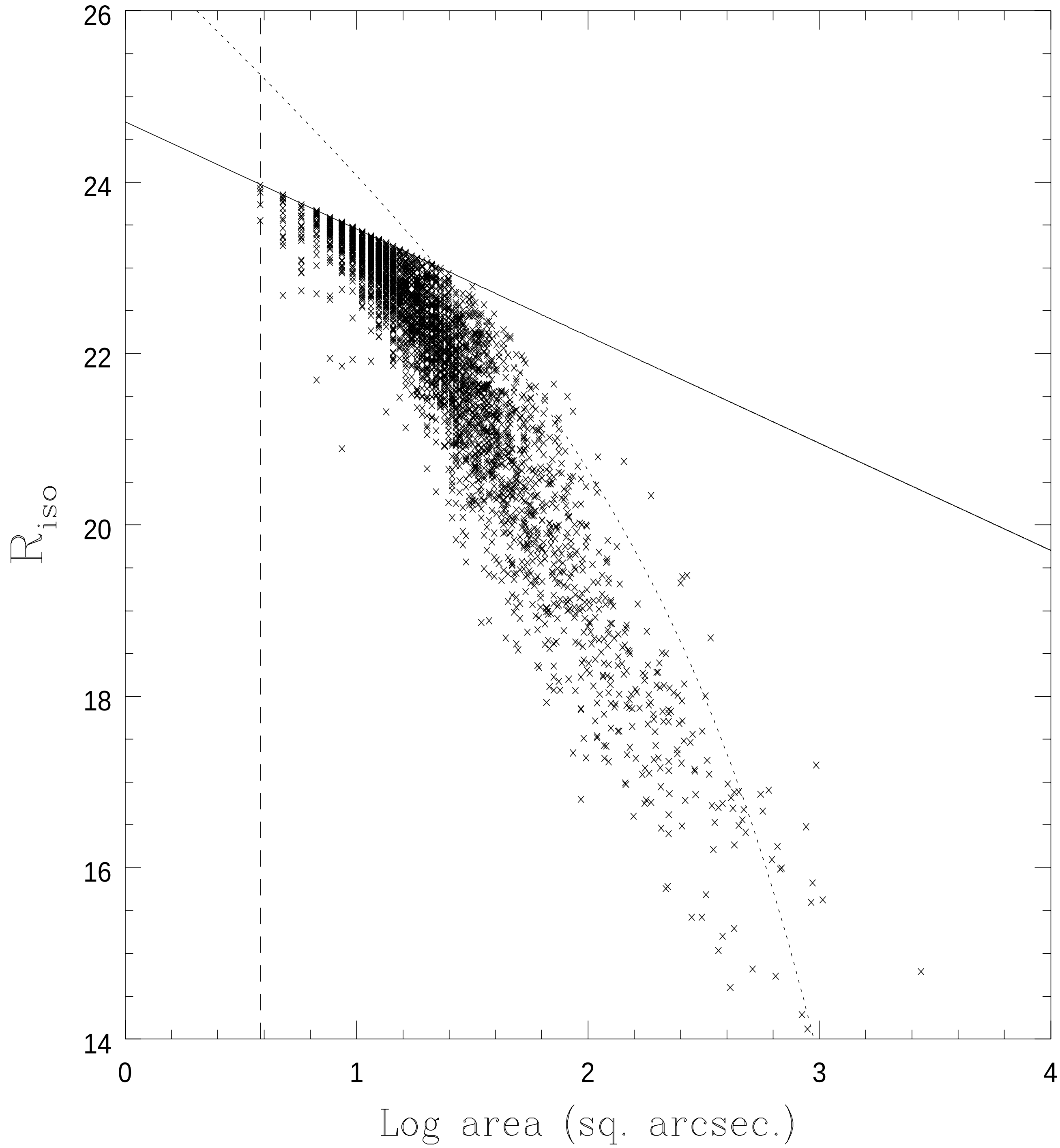
Figure 5. Integrated radial density profile of A 2554. The sample has been divided into two to represent the distribution of giants (circles) and dwarfs (triangles). The mean field density first subtracted and the data are scaled such that the total excess for giants or dwarfs is unity.

Figure 6. The isodensity structure of A 2554 for the giants (a) and the dwarfs (b) and for the blank control SGP field bright (c) and faint galaxies (d). The gray scale is set to display the overdense regions and the same scaling is used for all plots. The contours are as listed in the text. Fig. 6c mimics Fig. 6a showing that the dwarf galaxies are distributed like the giants but may have a flatter radial distribution. Figs 6b and 6d show that the structure seen for giants and dwarfs in A 2554 is significant when compared to the typical structure seen in a blank sight-line.

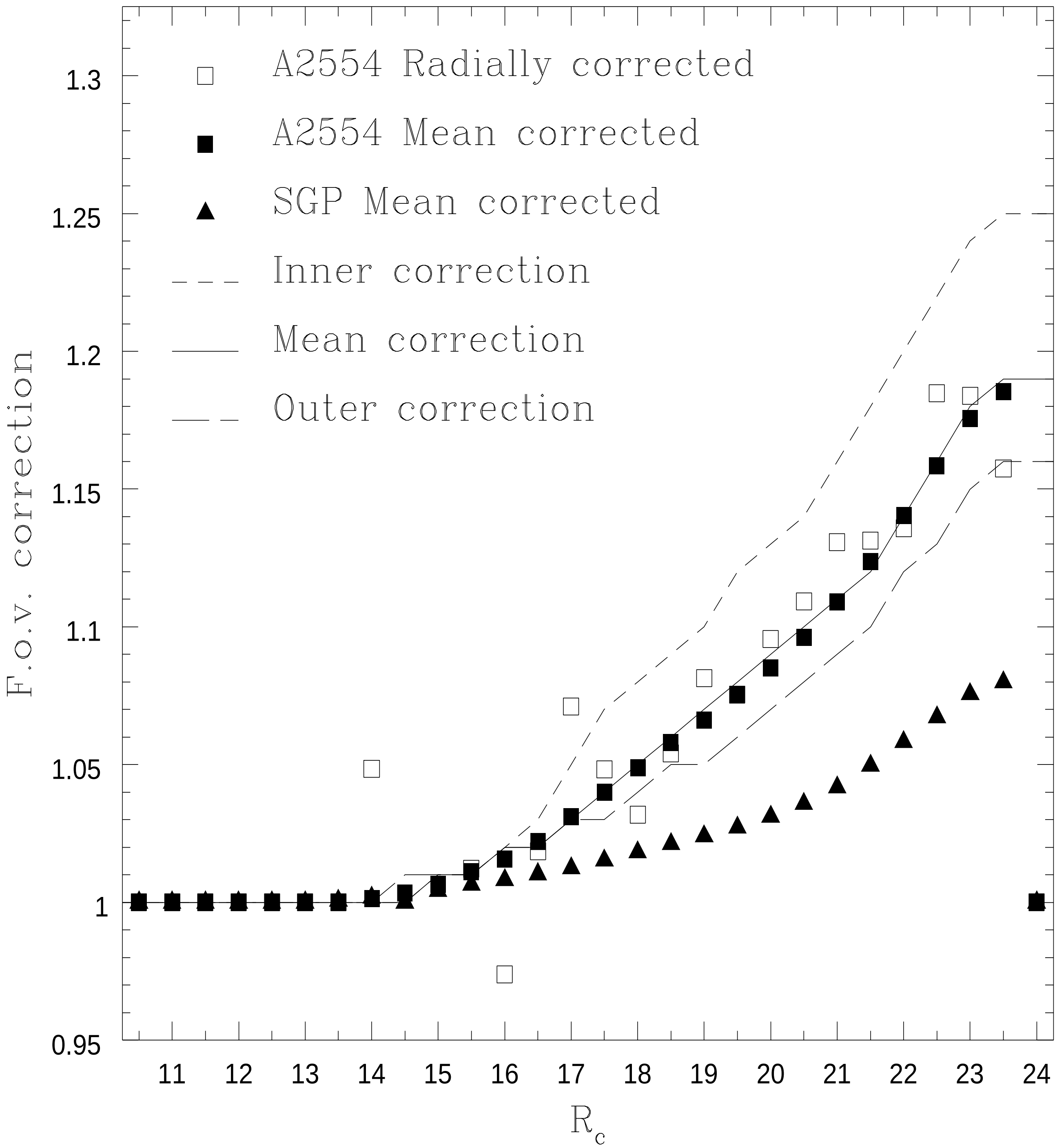
Figure 7. Comparison of the A 2554, A 963 and A 1367 (Coma) Cluster LFs. All

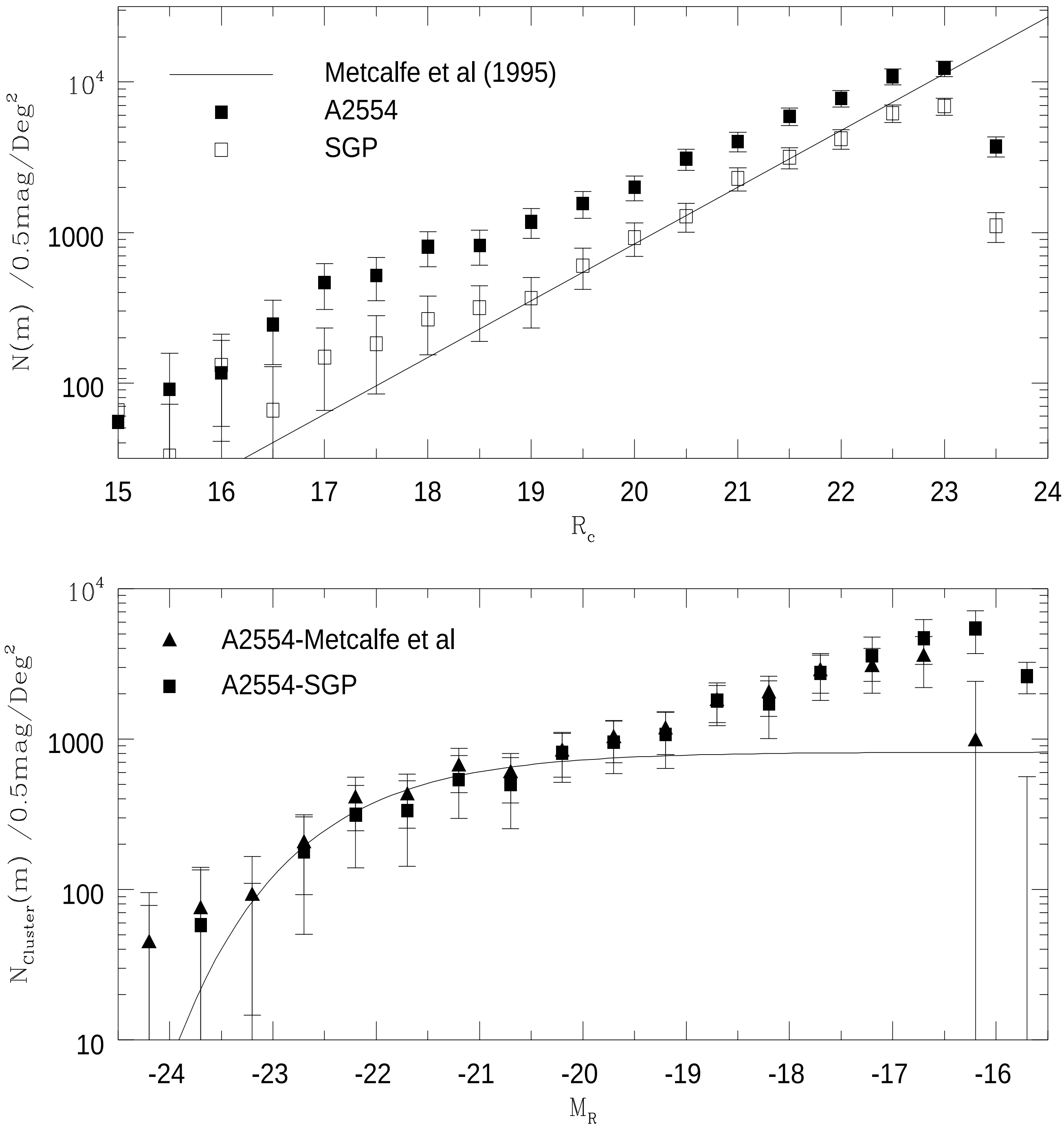
three clusters show a remarkable similarity in their galaxy luminosity distributions even though they span a wide range in redshift (0.02 – 0.2). The dotted line shows a Schechter LF with parameters $M^* = -22.5$ and $\alpha = -1.0$ whilst the dashed line is a Schechter LF with $M^*(R) = -19.5$ and $\alpha = -1.8$ and a ϕ^* of twice that of the dashed line.

FIGURE 1 not included

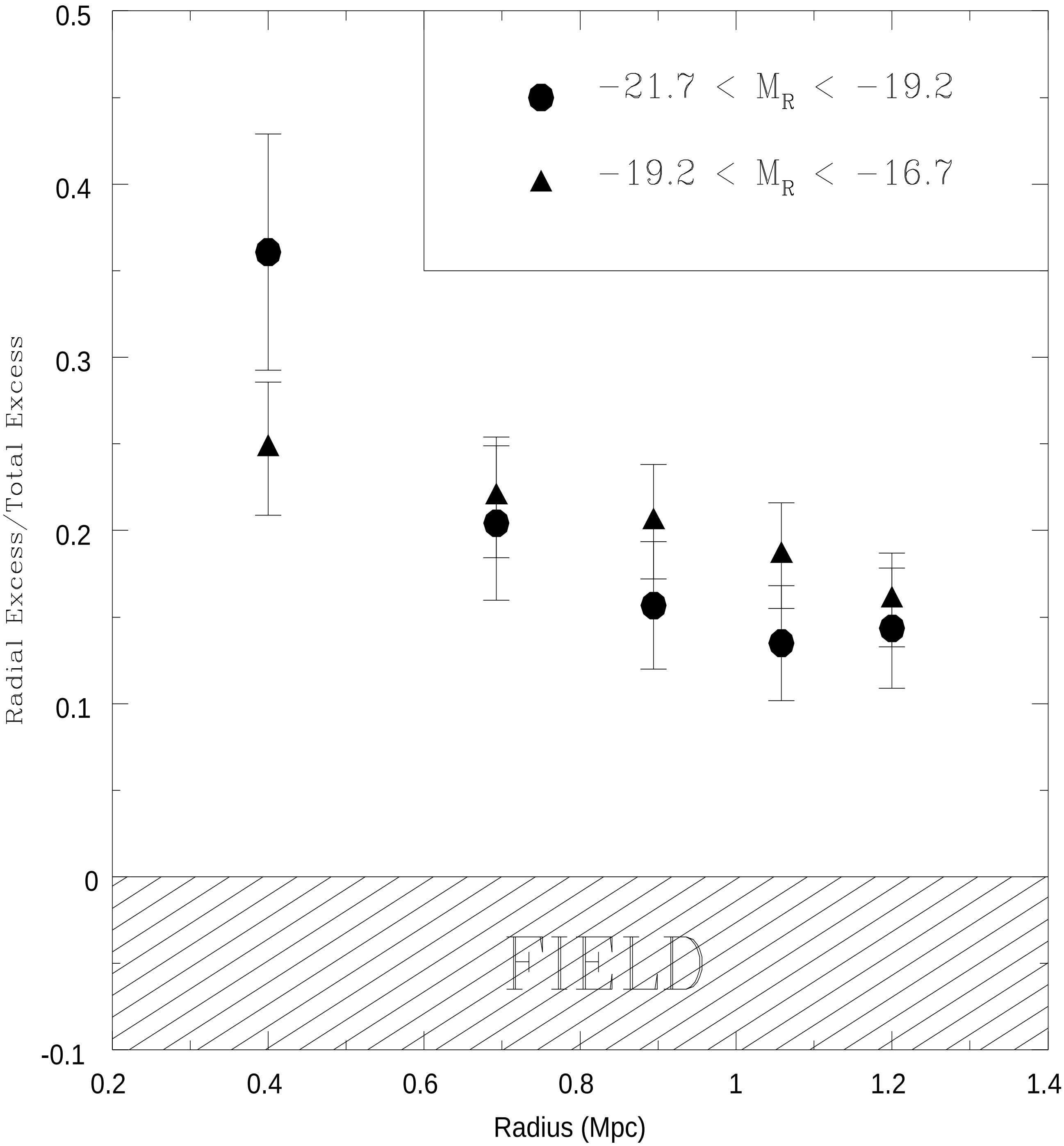


26
24
22
20
18
16
14
0
1
2
3
4
R_iso
Log area (sq. arcsec.)

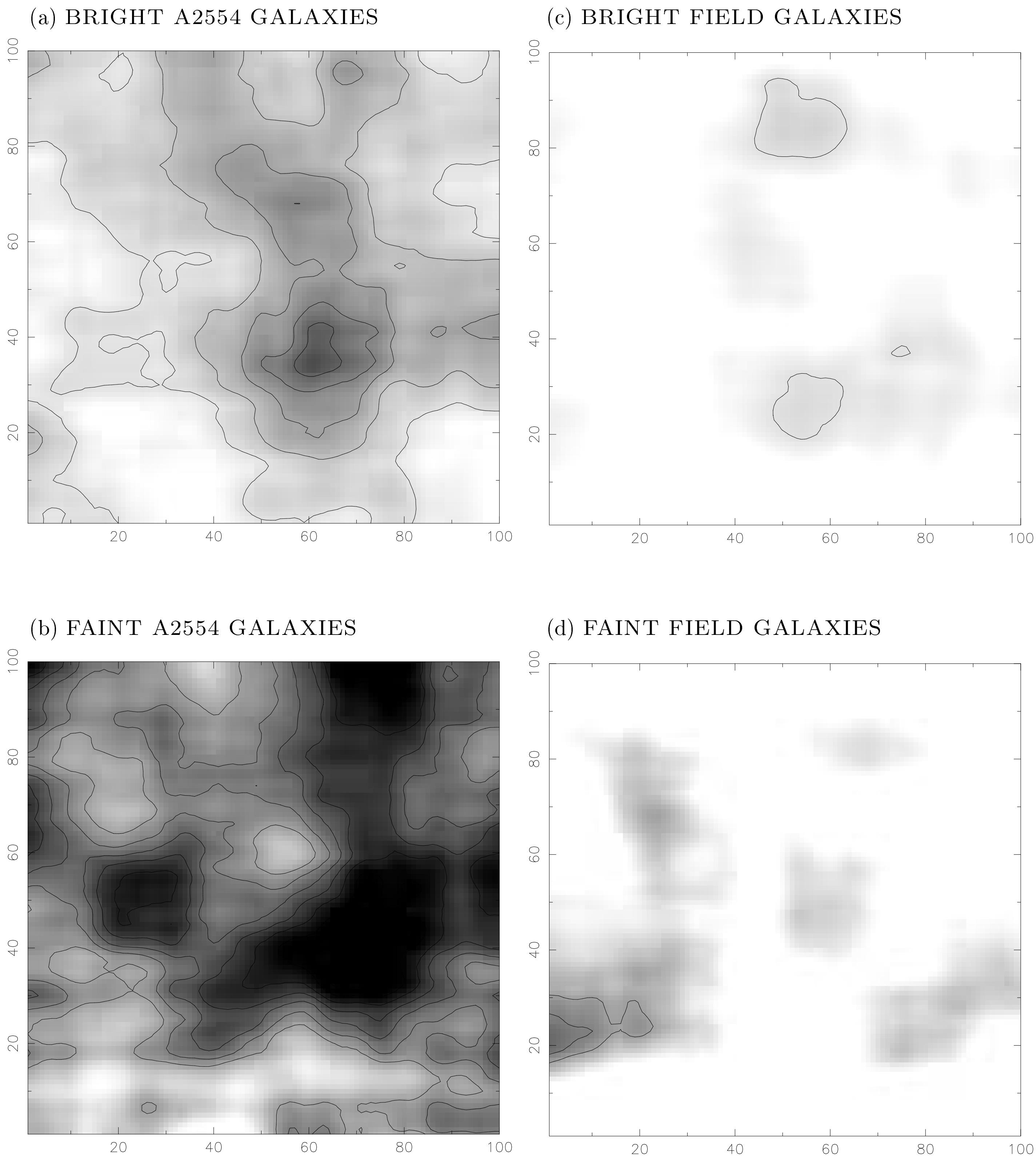

A2554 Radially corrected
A2554 Mean corrected
SGP Mean corrected
Inner correction
Mean correction
Outer correction
F.o.v. correction
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
11
12
13
14
15
16
17
18
19
20
21
22
23
24
R_c



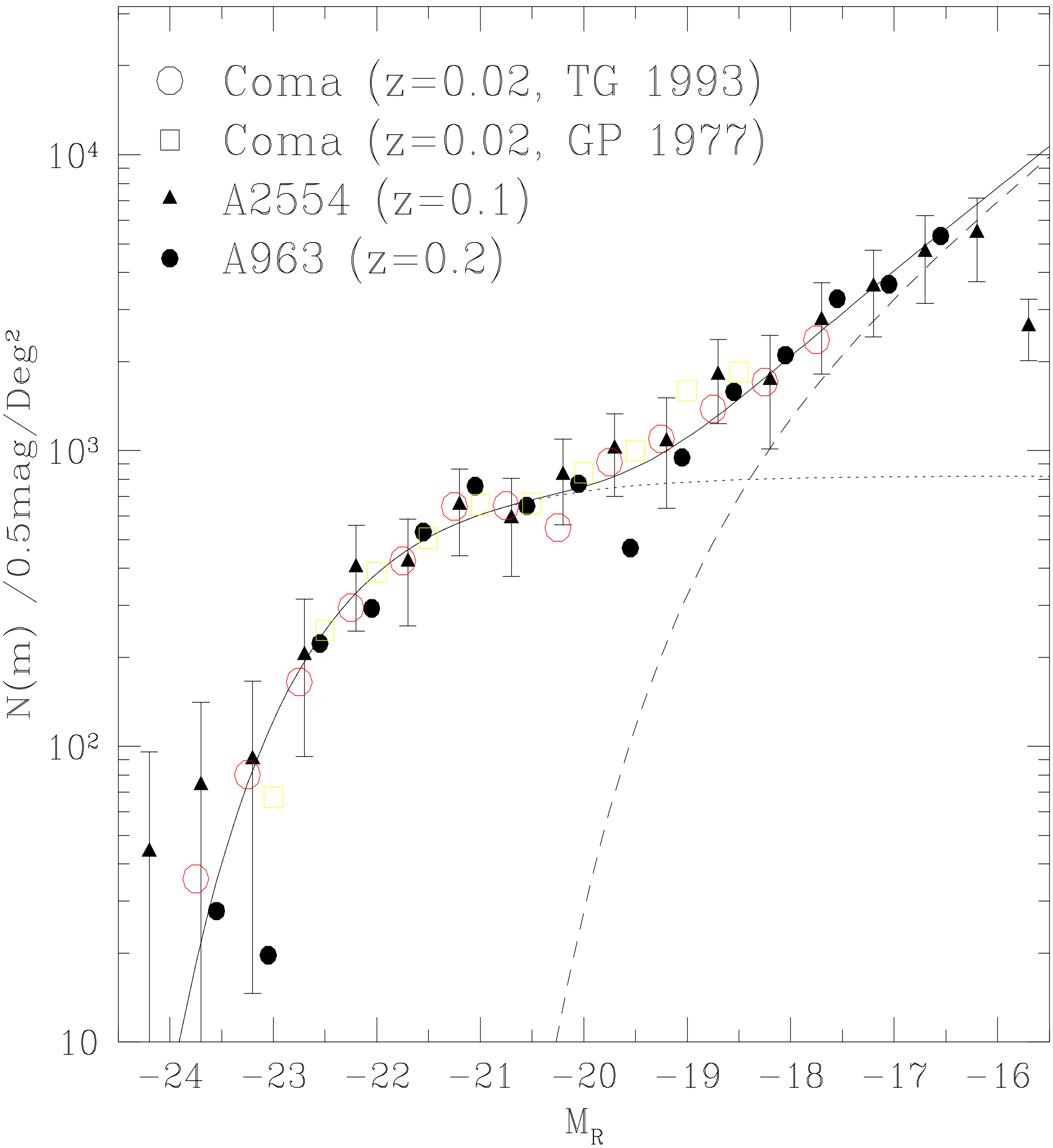
Metcalfe et al (1995)
A2554
SGP
N(m) /0.5mag/Deg^2
10^4
1000
100
15
16
17
18
19
20
21
22
23
24
R_c
A2554-Metcalfe et al
A2554-SGP
$N_{Cluster}$(m) /0.5mag/Deg^2
10^4
1000
100
10
-24
-23
-22
-21
-20
-19
-18
-17
-16
M_R



Radial Excess/Total Excess
0.5
0.4
0.3
0.2
0.1
0
-0.1
0.2
0.4
0.6
0.8
1
1.2
1.4
Radius (Mpc)
$-21.7 < M_R < -19.2$
$-19.2 < M_R < -16.7$
FIELD



(a) BRIGHT A2554 GALAXIES
(c) BRIGHT FIELD GALAXIES
(b) FAINT A2554 GALAXIES
(d) FAINT FIELD GALAXIES
20
40
60
80
100



Coma (z=0.02, TG 1993)
Coma (z=0.02, GP 1977)
A2554 (z=0.1)
A963 (z=0.2)
N(m) /0.5mag/Deg^2
10^4
10^3
10^2
10
−24
−23
−22
−21
−20
−19
−18
−17
−16
M_R